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WORK FOR THE AMATEUR ASTRONOMER[1]

II. *How To Build a Small Solar Observatory*

By George E. Hale

When I was a boy England surpassed all other countries as the home of the amateur in science. As explained in my first article, I regard the amateur, not in the sense of dilettante, but as one who works because he cannot help it, inspired by an inborn love for his subject which often appears at a very early age. Many of the leading English discoverers in astronomy, including Herschel, Carrington, Lockyer, and Huggins, carried on their work at home with instruments of their own contriving, in some cases made by themselves. Fortunately this country has also produced many such men, of whom Rutherfurd, Draper, Bond, Burnham, and Barnard are notable examples. During the last few years a surprisingly large number of American boys have become interested enough in astronomy to build telescopes for themselves. Some of these boys are satisfied by merely looking at celestial objects, which certainly afford abundant sources of pleasure. Others, moved by the spirit of the investigator, make valuable contributions to knowledge by recording the light-changes of variable stars, usually in cooperation with the American Association of Variable Star Observers. There are doubtless others who want a guide to astrophysical research, in which a taste for experiment aided, perhaps, by some mechanical ability, will play a useful part. It is for such boys that these papers are written.

I remember vividly my own lack of such guidance. I was fascinated by the marvelous views of rotifers and other infusoria

[1]The first article of this series appeared in these *Publications* in April, 1916. Shortly after it was written I was drawn into the work of the National Research Council. Service in the Council throughout the war and other causes have greatly delayed the completion of the series. Perhaps this is fortunate, because the recent development of the spectrohelioscope, which is particularly adapted for the use of amateurs, offers new opportunities in solar research.

under my microscope, but I wanted to *investigate* them—not merely to list the specimens found in various ponds and ditches—and I did not know how to go about it. I did contrive to couple my microscope with a camera, and thus make photomicrographs of various objects, but this was not research. I collected fossils from the limestone rocks that filled the breakwaters of Lake Michigan, and so became interested in evolution, but I did not see how I could add anything of importance to its study. My books told me how to make this and that experiment in chemistry and physics, and no one could enjoy them more than I did. But what I wanted was a description that I could follow of *a connected series of experiments*, leading step by step to the development of some branch of science and giving a clue to the nature of research.

My microscope, however, had taught me two of the most important principles underlying original research: first, that invisible worlds, full of the most beautiful and intricate phenomena, lie all about us, offering endless possibilities for investigation; and second, that special instruments and methods may be devised for rendering them accessible to study. Thus I was prepared, when I improvised my first crude telescope, to appreciate a little more clearly the steps open to the investigator.

When I had finally obtained a 4-inch telescope, and mounted it upon a heavy brick wall so that it projected above the roof of the house and afforded an unobstructed view of the sky, I was delighted with all that it showed me. But after observing night after night the long range of celestial objects, and finding them (as it seemed) so completely described in my books, the desire to learn something new and the need of a guide became more insistent than ever. It was evident that photography offered limitless opportunities, and as my telescope had no driving-clock I first tried my hand on the Sun. About this time I began to read of the spectroscope and to perceive dimly that of all the allies of the astronomer this comparatively new instrument, if aided by photography, offered more promise than any other.

Even now I cannot think without excitement of my first faint perception of the possibilities of the spectroscope and my first glimpse of the pathway, which rapidly became clearer, thus suggested for me.

The two books to which I look back with the greatest pleasure are Lockyer's *Studies in Spectrum Analysis* and the *Contributions to Solar Physics* of the same author. The reproductions of photographs of solar and metallic spectra in the first of these volumes determined me to make similar photographs, and the contact with original discovery afforded by the *Solar Physics* aroused my own desires in this direction as nothing else had previously done. Here I learned another fundamental principle, of vital importance to beginners in research. Acquire the habit as early as possible of going to the original sources, where you may read the first records of great discoveries in the words of the men who made them. Thus I became acquainted with the *Proceedings* and the *Philosophical Transactions* of the Royal Society of London and the *Comptes Rendus* of the Paris Academy of Sciences. I had toiled painfully through my Latin, but with this incentive it became clear that I must learn French without delay. So I soon found myself at home among these pages and I thereby acquired an admiration for the Royal Society and the Paris Academy as centers and promoters of research which has had much to do with some of my later work.

I am dwelling too long on old memories, but I have a definite object in view. I want to advise every boy interested in solar research to read these very same books, especially Lockyer's *Solar Physics*, as they are of the type that never get out of date. I also want to emphasize the pleasure and profit of looking up the original sources of scientific literature, to be found in any large public library. The old volumes are almost as interesting as the later ones, and I never used time to better advantage than in going through volume after volume, making abstracts of all interesting papers in my note-book.

But I must pass to matters of more immediate interest. My plan is to tell first how to build an inexpensive solar telescope, which can be used for observing sun-spots and recording their positions and forms as they vary from day to day. (Fig. 1). The next instrument needed is a spectroscope, and I have designed a simple but powerful one, which can also be turned into a spectrohelioscope or spectroheliograph for visual and photographic observations of the solar atmosphere. Our first use of the spectroscope, however, will be to observe and photograph various parts of the solar spectrum, and to determine the presence in the Sun's atmosphere of such elements as sodium, iron, and hydrogen. This will introduce us to the laboratory side of astrophysical research, which has grown immensely more interesting and important in recent years because of the rapid development of modern physics.

We may then turn to an examination of certain lines of hydrogen and helium at the Sun's circumference, and repeat for ourselves the classic experiment which enabled Janssen and Lockyer in 1868 to detect the red flames in the solar atmosphere in full sunlight, without waiting for a total eclipse. We may also follow them in their next step, and by widening the slit of the spectroscope see the forms of the prominences rising above the edge of the Sun.

The gases in the solar atmosphere are rarely at rest, and their rapid movements are shown in the spectrum by the displacement or distortion of their lines. By measuring these displacements we can determine the velocity of the gases toward or from the Earth, and also utilize this method as a means of learning the speed of the Sun's axial rotation at different levels.

At this stage, following the work of the early nineties, we may adopt photographic methods to disclose that portion of the solar atmosphere which is projected against the brilliant disc. By a simple device we transform the spectroscope into a spectroheliograph, which will give us photographs of the prominences at the limb and the low-lying bright clouds of calcium vapor, called flocculi, that cover large areas on the disc, especially within the sun-spot zones.

The same method will record the bright and dark hydrogen flocculi against the disc and reveal the immense vortices or cyclonic storms that surround sun-spots. By changing the spectroheliograph into a spectrohelioscope, we can render visible these hydrogen flocculi, watch their rapid changes, and quickly measure their radial velocities and analyze their structure. Moreover, we can easily see with the spectrohelioscope, even through the smoky air of a large city, the brilliant eruptions on the Sun's disc that occasionally forecast the occurrence on the Earth of auroras, magnetic storms, and variations in radio transmission. Here is an opportunity for research in a field so little studied that it should particularly appeal to amateurs who want to add something to knowledge.

A SIMPLE SOLAR TELESCOPE

The first of our needs is a simple but effective solar telescope. If one wishes merely to see sun-spots, an ordinary refracting or reflecting telescope, with movable tube directed toward the Sun, will serve very well. But for the work we have in view, which requires the use of a spectroscope thirteen feet long, such an instrument is evidently unsuited. For the spectroscopic observations we must have a solar image about two inches in diameter, held in a fixed position by a driving-clock.

A single mirror polar heliostat may be used, sending the sunlight toward the north or south pole, but it will usually be more convenient to mount the long spectroscope horizontally or vertically rather than at such an angle. The polar heliostat also has the disadvantage of causing the solar image to rotate slowly, though for most work this is not a serious objection. An ordinary laboratory two mirror heliostat will send the beam in any direction, and should serve very well if the mirrors are silvered on their front surfaces, which should be plane to about one quarter of a wave. The instrument I have chosen, however, is the coelostat, similar to the larger one in my Solar Laboratory at Pasadena, but very simple to build and serviceable in practice. The solar image obtained with its aid does not rotate, and the adjustments are easily made.

The coelostat[2] consists of a plane mirror of plate glass, 5½ inches in diameter and ½ inch thick, mounted with its surface

[2]The design of this small coelostat is largely due to Captain Lorenzo Snow, who took an active part in this work before the war. I am indebted to my instrument maker, Mr. Hitchcock, and to Messrs. Pease and Nichols of the Mount Wilson Observatory, for their valuable aid in developing the complete design of the solar telescope and spectrohelioscope.

parallel to the Earth's axis and uniformly rotated by an ordinary (two dollar) clock movement at the rate of one complete revolution in 48 hours. (Fig. 2.)

The parallel rays of sunlight reflected from the silvered front surface of the coelostat mirror fall on a second mirror of plate glass, 4½ inches in diameter and ½ inch thick, mounted in a fork and provided with slow-motion screws controlled by the observer with rods or cords. This mirror is fixed during observation, but the slow motions permit the observer to move it sufficiently to bring any point on the Sun's disc or circumference to the center of the slit of the spectrohelioscope.

These two mirrors of course do not form an image of the Sun. They serve merely to send the parallel rays in a chosen direction (usually north) and to hold them there during observation. The solar image is formed by a single plano-convex lens 3 or 4 inches in diameter and of 18 feet focal length, mounted on a support which can be moved north or south with a coarse screw by the observer for focussing the image on the slit. Such a lens is suitable only for spectroscopic observations covering a limited range of wave-length and for observations of the prominences and flocculi with monochromatic light. An achromatic lens or a long focus concave mirror is needed for direct observations of sun-spots in white light.[3]

The coelostat, second mirror, and lens are shown in Fig. 2, temporarily mounted on a wooden tripod south of a small garage containing the spectrohelioscope. For permanent use a brick or concrete pier, covered with a small wooden house easily removable when observations are to be made, should be erected as a more stable base. The coelostat may stand either east or west of the second mirror support (out of its shadow), but on account of the varying altitude of the Sun, it must be moved north or south and fixed for any given date at a point where the reflected beam

[3]A small telescope having an achromatic lens about two inches in diameter, with eyepiece permitting a solar image from four to six inches in diameter to be projected upon a white card for recording the positions of sun-spots, will serve as a useful substitute for the single lens. The larger spots can be fairly well seen, however, on the 2-inch image given by the single lens, especially if it is looked at on a white card through dark spectacles supplemented by a piece of red glass.

falls on the center of the second mirror. The beam is then maintained in place by the driving clock.

Another photograph of this solar telescope, as made from our drawings by Howell & Sherburne,[4] is shown in Fig. 7. It would be convenient to fasten a pair of rails, or merely a single guiding strip of metal, to the top of the pier both east and west of the second mirror, so that when the coelostat is moved north or south its polar axis will be held by them in the meridian. A set of blue-prints giving complete working drawings of this instrument may be obtained at nominal cost by addressing the Mount Wilson Observatory, Pasadena, California. These will enable any amateur having a small shop to build the metal parts for himself. As for the optical parts, these may be purchased from an optician, or made by the amateur in accordance with the directions given in *Amateur Telescope Making*, an admirable little book soon to be issued in a revised and enlarged second edition by the Scientific American Publishing Company, New York.

The first edition of this book includes a picture of a simple alt-azimuth mounting, carrying a plane mirror, which Mr. Russell W. Porter uses to reflect a beam of sunlight to a long focus concave mirror giving a large image of the Sun in a house. Such an arrangement will show sun-spots very well but will not keep the image at rest. It is evident that the outfit shown in Fig. 2 could be modified so as to reflect the beam from the coelostat south instead of north. It could then be received, as in Mr. Porter's arrangement, by a long-focus concave mirror and returned north into the house through a larger hole. Or, as suggested in the footnote on page 290, a small achromatic telescope with eyepiece to enlarge the image could be set up in the house when a large direct image of the Sun is wanted to show the spots and record their positions.

I need not describe the appearance or characteristics of sunspots, as these may be found in such books as Lockyer's *Solar Physics*, Young's *The Sun*, Secchi's *Le Soleil*, Langley's *New Astronomy*, and Abbot's *The Sun*. The simplest way to record their positions (heliocentric latitudes and longitudes) is with the aid of a set of the Stonyhurst cardboard discs (Fig. 3), ruled

[4]88 North Delacy Street, Pasadena, California.

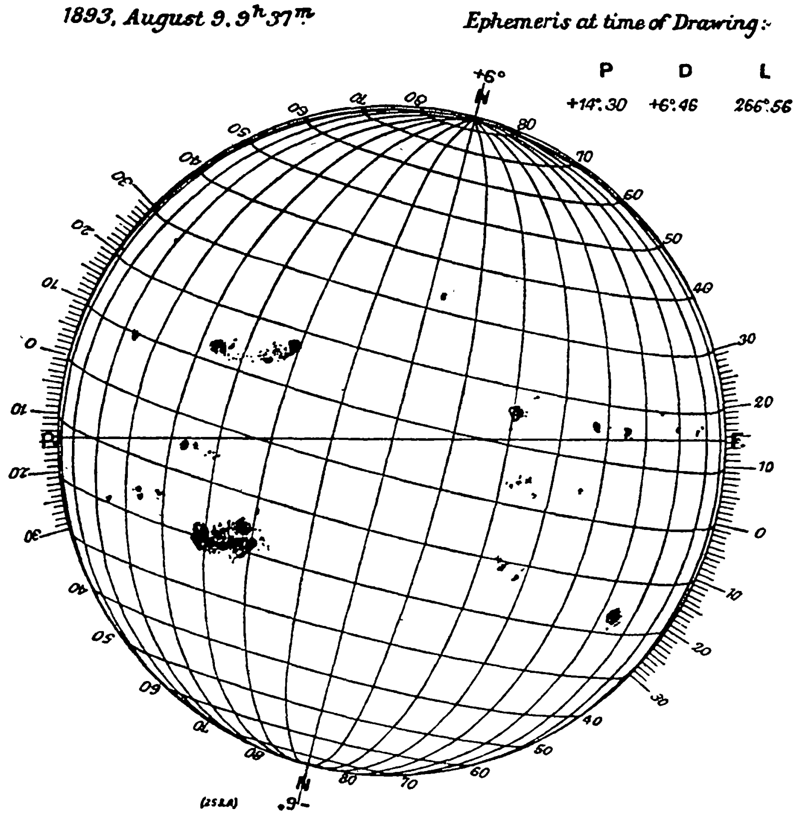

Figure 3
Illustrating the use of a "Stonyhurst Disc."

with meridians and parallels, obtainable from Casella & Company, Parliament Street, London, S. W. 1.[5] The changes in position of the spots from day to day, due chiefly to the Sun's axial rotation and in part to their own proper motion, are thus easily measurable. Such a record will enable the amateur to determine for himself the peculiar law of the Sun's rotation, and to compare the velocities given by the motions of the spots in different latitudes with those of the gases at various levels in the solar atmosphere obtained by spectroscopic measurements. Moreover, unless a set of daily direct photographs of the Sun is available, the spot drawings will be of the greatest service in the study of the prominences and flocculi, which cannot be effectively investigated without a knowledge of the spots with which

[5]For an excellent account by the late Father Cortie of the use of the discs, see "The Stonyhurst Discs for Measuring the Positions of Sunspots," *Memoirs British Astronomical Association*, Vol. 23, Part II, 1921.

they are so often associated. While it is true that individual spots can easily be seen with the spectrohelioscope, merely by setting the second slit on the continuous spectrum near the red hydrogen line, a diagram of the whole Sun, with the spots outlined in their respective positions, is usually needed in researches on the solar atmosphere.

As for direct photographs, these can be taken of a solar image formed by a long-focus concave mirror, but if this image is too large the spots are likely to be badly defined because of poor seeing due to atmospheric disturbances. A diameter of about four inches will usually be found satisfactory. The focal plane shutter needed for direct photography, which consists merely of a screen bearing a slit and arranged to shoot rapidly across the solar image, just in front of a photographic plate, is illustrated in some of the books already mentioned. It is not likely to give good results with a solar image formed by an achromatic lens and enlarged by an eyepiece, unless a suitable colored screen is used or both lens and eyepiece are especially designed for photographic work.

The amateur is strongly advised to go back into the original literature and look up the papers on sun-spots by Sir William and Sir John Herschel, Carrington, Dawes, De La Rue, Lockyer, Huggins, Young, Langley, Sidgreaves, Cortie, Maunder, and many others. He will find them referred to in some of the books I have cited and in Miss Clerke's admirable *History of Astronomy During the Nineteenth Century*, which all amateurs should read.[6]

A SOLAR SPECTROSCOPE AND ITS USE

The solar telescope illustrated in Figs. 2 and 7 is no mere toy, in spite of its simplicity and cheapness. As a matter of fact, I have tried substituting this small coelostat and second mirror for the much larger ones of my Solar Laboratory, and could see no material change in the quality of the solar image when examined with the spectrohelioscope. In the same way the spectroscope (transformable into a spectrohelioscope) now to be de-

[6] I have referred here only to some easily accessible papers in English, but those in other languages should not be neglected. The early observations of Galileo, which are of the greatest interest, are summarized by Walter M. Mitchell in "The History of the Discovery of the Solar Spots" in *Popular Astronomy*, Vol. 24.

scribed, though equally simple in construction, is really a powerful instrument of research, with which a wide range of original investigations can be made. I shall make no attempt to explain all of its uses, leaving the reader to learn most of them for himself from such old but very useful books as Roscoe's *Spectrum Analysis* (my copy is of the fourth edition, revised and enlarged by Schuster), and Schellen's *Spectrum Analysis*, translated by Lassell. These volumes, dating from the early days of spectroscopy, contain many details of special value to the amateur, which are omitted or greatly condensed in more recent books. Of these, Baly's *Spectroscopy* brings the subject (on the terrestrial side) nearly up to date, giving in the third volume a most interesting sketch of its recent marvelous transformation from a purely empirical into a rational science, and showing the vital part spectroscopy has played in the development of our knowledge of the structure of the atom and the constitution of matter. Kayser's great *Handbuch der Spectroscopie*, intermediate in date, includes a vast mass of invaluable information. On the astrophysical side I shall refer now merely to Stratton's excellent *Astronomical Physics* (Dutton, 1924).

My purpose here is to describe a solar spectroscope of a type readily adaptable for use as a spectrohelioscope. If desired solely as a spectrograph, its form would be different, because the present instrument gives only a short range of spectrum on a photographic plate. But for visual work in any part of the spectrum and for monochromatic observations of the Sun, this arrangement is an extremely satisfactory one, while it will serve very well for the photography of limited regions, especially as the focus does not change in passing from one wave-length to another.

Fig. 4 shows the path of the rays in the spectroscope. The slit (Fig. 5) receives light from any part of the two-inch solar image and transmits it to the concave collimator (upper mirror) (Fig. 8).[7] This renders the diverging rays parallel and returns the beam to the grating (Fig. 7), which is turned about its vertical axis to such an angle as to send the diffracted rays corre-

[7]The photographs reproduced in Figs. 6, 7 and 8 were kindly supplied by Messrs. Howell & Sherburne, makers of these instruments.

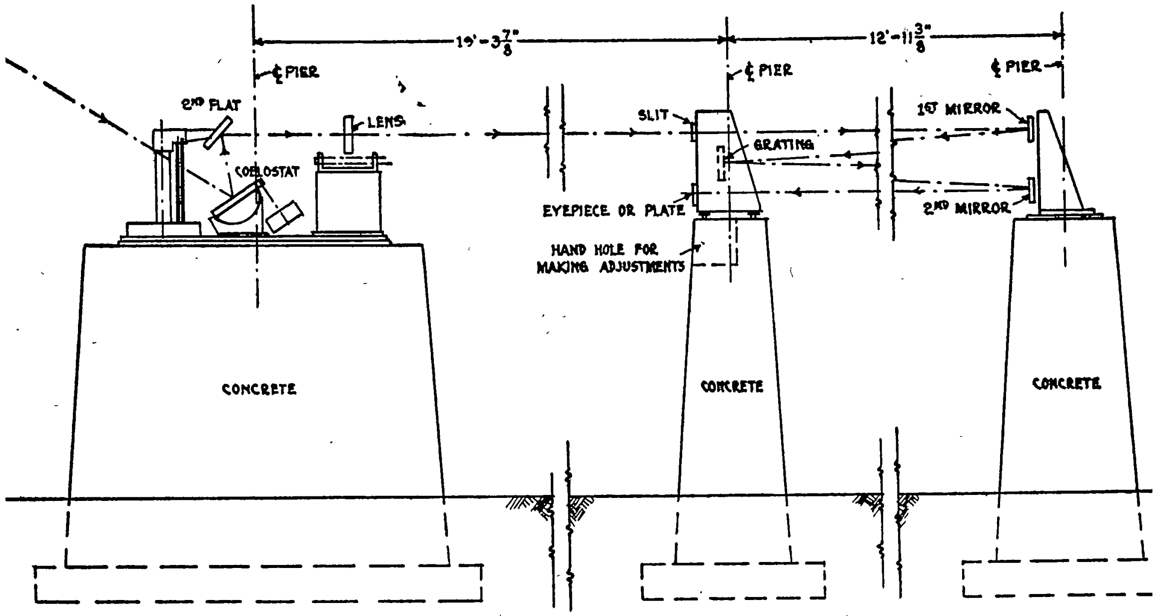

Figure 4

Elevation of Solar Telescope and Spectroscope. The coelostat, second flat, and lens of the horizontal telescope are mounted on a solid pier in the open air. The spectroscope stands on two piers in a dark room, where the observations are made. By means of simple attachments the spectroscope can be instantly converted into a spectroheliograph or spectrohelioscope for photographic or visual observations of the solar atmosphere.

sponding to any desired region of the spectrum to the lower concave mirror. This mirror forms an image of this portion of the spectrum at a point below the slit, where an eyepiece or photographic plate-holder is fixed. By slowly rotating the grating about its vertical axis the whole range of the spectrum can be passed in review. Moreover, by turning it through a greater angle the second, third, or fourth order spectrum, of higher and higher dispersion and (usually) of rapidly decreasing brightness, can be observed.

The casting that carries the slit, grating, and eyepiece, and a second one bearing the spherical concave mirrors, are firmly mounted in a dark room on concrete piers nearly 13 feet (the focal length of the concave mirrors) apart. A black screen of sheet metal should be set up between them, in such a way as to shield the eyepiece or photographic plate from the diffuse light of the collimating mirror without interfering with the course of the rays falling upon the grating and the lower mirror.

With a good grating and a slit-width of one or two thousandths of an inch, the solar spectrum thus obtained is a superb spectacle. The room must be made as dark as possible by enclosing the beam of sunlight from the opening in the wall to the slit. When this precaution is taken the gorgeous band of the spectrum, crossed with thousands of lines of various widths and intensities, may be seen in all its purity from the extreme red to the limits of the violet. No other research can surpass in interest and importance that of interpreting the mysteries concealed in these lines. Their positions and intensities, and the extraordinary changes they may undergo as the result of variations in the physical or chemical state of the vapors that produce them, afford the chief clue to the nature and evolution of the Sun and stars, and to the constitution of matter itself.

I shall never forget my first view of the solar spectrum under high dispersion. Forty years ago I set up in my laboratory at Kenwood, a suburb of Chicago, a 4-inch Rowland concave grating. In the form of mounting devised by Rowland it is admirably adapted for photographing long ranges of the spectrum on a single plate, but for our present needs its astigmatism, which mixes up the light from various parts of the solar image, would render it unsuitable. In the intense darkness of the grating-room, completely separated by a partition from the small room in which the slit was mounted, and with its walls painted dead black, the sight of the spectrum was marvelous. The precision of measurement thus afforded, and the closeness and actual overlapping of many solar lines, even with the high dispersion of the fourth order spectrum, taught me more than one fundamental principle, which I have never forgotten in designing telescopes, observatories and laboratories.

The metal parts of this spectroscope are simple and easily made,[8] and the concave mirrors can be obtained at moderate cost or made by the amateur himself. The grating recom-

[8]A set of blueprints giving complete drawings of this instrument and of the additional parts needed to transform it into a spectrohelioscope, may be obtained at cost from the Mount Wilson Observatory, Pasadena, California.

mended has a plane polished surface of speculum metal about four inches in diameter, on a rectangular area of which lines are ruled with a diamond at the rate of about 14000 or 15000 to the inch. Such gratings diffract the white light of the Sun into a series of spectra, and in the red region, near the Hα line of hydrogen used with the spectroheliоscope, their dispersion in the first order is much higher than that of a prism. In fact, two prisms of light flint glass, through which the light from the collimator passes to a plane mirror, which returns the rays through the prisms to the second concave mirror, give a dispersion in the red far below that of the grating, though the effect of this arrangement is equivalent to that of four prisms. If a grating cannot be obtained from J. W. Fecker,[9] 1954 Perrysville Avenue, Pittsburgh, Pennsylvania, or from Adam Hilger, Ltd., 24 Rochester Place, London, N. W. 1, England, two very dense flint glass prisms, of 60° angle, will serve very well for spectroscopic work, though for use with the spectroheliоscope they are much inferior to a good grating, if my experience with less dense prisms can be trusted.

We are endeavoring to find some process by which inexpensive replicas or perfect copies of original gratings can be made. But the difficulties are great, and as yet they have been only partially overcome. The best promise of good reflecting replicas seems to lie in an electrolytic process, which deposits some highly reflecting metal upon an original grating. When stripped off, however, the surface has always been warped, though the lines are beautifully reproduced and the spectrum is brilliantly shown. Anyone who can completely solve this problem will make a great contribution to spectroscopy and to general optics, for there is no reason why plane and concave mirrors, with untarnishable faces of various metals, should not be cheaply produced from originals in the same way.

[9]The price of plane gratings ruled at Johns Hopkins University and sold by Fecker is \$200 for a 4-inch and \$125 for a 2½-inch grating, the latter with ruled surface about 1½ x 2 inches. The larger size (which should be very bright at Hα in the first order) should be obtained if possible, but the smaller grating, if very bright in the same region, should show all of the larger and more intense flocculi. Hilger sells similar gratings (catalogue numbers K15 and K14), ruled at the National Physical Laboratory.

ADJUSTMENTS OF THE INSTRUMENTS

As already stated, the polar axis of the coelostat should point to the true pole, and the rails along which it slides should be set closely north and south. A horizontal line running due north through the center of the second mirror of the coelostat should pass through the centers of the telescope lens, the slit about 18 feet from it, and the upper concave mirror nearly 13 feet farther north. When filled with sunlight from the slit, this concave mirror should be adjusted by its three screws until the nearly parallel beam returned from it falls centrally upon the grating, standing vertically, with its face in an east and west plane. The beam of white light reflected north from the grating should then fall upon the lower concave mirror, which is next adjusted until an image of the slit, in white light, falls at the center of the photographic plate.

When examining this direct image with an eyepiece, the intensity of the light should be reduced by means of a piece of very deep red glass (in contact with the slit). The casting that supports the two concave mirrors should then be moved north or south by the focussing screw until the image of the slit is sharp on the plate. The easiest way to assure this is to scrape off part of the film of an unexposed plate, fix it in the plane that the face of the plate in its holder will occupy, and examine the slit-image through the clear glass with a lens or positive eyepiece magnifying about ten diameters focussed upon the film. By means of the fine adjusting screw the lower concave mirror should then be tipped a little, if necessary, to bring the image of the center of the slit exactly to the center of the plate.

The next adjustment is made by rotating the grating until the red region containing Hα in the brightest first order spectrum falls centrally upon the lower concave mirror, which should be the case when the Hα line appears in the field of the eyepiece. If the center of the spectrum is too high or too low, this probably results from the fact that the rulings of the grating are not exactly vertical (assuming, of course, that the grating cell and its bearing are properly made, and that the supporting casting has been set up accurately, with this bearing vertical.) The grating must therefore be rotated in its cell by the adjusting screws until the directly reflected image of the slit and the Hα line in the first order lie in the same plane. In this case the spectra of the various orders, which can be seen on the wall behind the concave mirrors if a wide first slit is used, appear in a horizontal line.

For accurate focussing the first slit should be made very narrow and the concave mirrors moved by the focussing screw until the narrowest lines in the spectrum appear perfectly sharp. The horizontal lines running through the spectrum, due to dust on the slit, should also appear sharp at the same focus. If either the spectrum lines or dust lines are not sharp, the grating may be slightly warped by the screws that hold it in its cell. These should bear against small pieces of cardboard and must not be too tight, though the grating should be held firmly enough to prevent vibration when the oscillating slit of the spectrohelioscope is running.

Without going into further details we may now pass on to the use of the spectroscope.

ANALYSIS OF SUNLIGHT

The second proposition in Newton's *Opticks*, entitled "The Light of the Sun consists of Rays differently Refrangible," describes his famous experiment of analyzing sunlight with a prism:[10] "In a very dark Chamber at a round hole about one third part of an Inch broad made in the Shut of a Window I placed a Glass Prism, whereby the beam of the Sun's Light which came in at that hole might be refracted upwards toward the opposite Wall of the Chamber, and there form a coloured Image of the Sun. The Axis of the Prism (that is the Line passing through the middle of the Prism from one end of it to the other end Parallel to the edge of the Refracting Angle) was in this and the following Experiments perpendicular to the incident Rays. About this Axis I turned the Prism slowly and saw the refracted Light on the Wall or coloured Image of the Sun first to descend and then to ascend. Between the descent and Ascent when the Image seemed Stationary, I stopt the Prism, and fixt it in that Posture, that it should be moved no more." (page 18). This position of minimum deviation is almost invariably used in

[10]The quotations are from my copy of the first edition, London, 1704.

the adjustment of prism spectroscopes. I advise the reader to look up the rest of the account for himself and to observe the care taken by Newton to avoid errors or misinterpretations due to defects in his apparatus or to imperfect experiments.

Noting (page 47) that "if we would diminish the mixture of the Rays we are to diminish the Diameters of the Circles" (the holes through which the light enters), Newton saw the advantage of using a different arrangement: "In the Sun's Light let into my darkened Chamber through a small round hole in my Window-shut, at about 10 or 12 Feet from the Window, I placed a Lens, by which the Image of the hole might be distinctly cast upon a sheet of white Paper, placed at the distance of six, eight, ten, or twelve Feet from the Lens" (page 47). He thus obtained the arrangement shown in his Fig. 24, Plate V, which gave a much purer spectrum. He then realized that a slit would serve still better: "Yet instead of the circular hole F, 'tis better to substitute an oblong hole shaped like a long Parallelogram with its length Parallel to the Prism A B C. For if this hole be an Inch or two long, and but a tenth or twentieth part of an Inch broad or narrower: the Light of the Image pt will be as Simple as before or simpler, and the Image will become much broader, and therefore more fit to have Experiments tried in its Light than before" (page 49).

In spite of all the precautions described in pages 50 and 51, whether because of imperfect glass and surfaces, or incomplete, polish "such as is usually wrought with Putty, whereby the edges of the Sand-holes being worn away, there are left all over the Glass a numberless company of very little Convex polite risings like Waves," even so great an experimenter as Newton failed to detect the dark lines of the solar spectrum. Except for Melville's important observations in 1752 through a prism of an alcohol flame containing the vapors of alum, potash, and other substances,[11] which foreshadow the study of emission spectra, little or nothing was added to our knowledge of the spectrum until after the lapse of a century, when Sir William Herschel and J. W. Ritter respectively discovered the extension of the solar

[11]See his papers reprinted in the *Journal of the Royal Astronomical Society of Canada*, July and August, 1914.

spectrum beyond the red (by its heating effect),[12] and beyond the violet (by its effect in blackening silver chloride).[13]

In 1802 Wollaston repeated Newton's experiment, probably with a much better prism, and detected certain dark lines crossing the solar spectrum, which he considered to be boundaries of the various colors: "If a beam of daylight be admitted into a dark room by a crevice 1/20 of an inch broad, and received by the eye at a distance of 10 or 12 feet, through a prism of flint glass, *free from veins*, held near to the eye, the beam is seen to be separated into the following four colours only, red, yellowish green, blue and violet." Unfortunately, Wollaston did not follow up his discovery, and it remained for Fraunhofer in 1814 to describe and map hundreds of lines in the solar spectrum, which he recognized as in no sense marking the limits of the various colors.

The "Fraunhofer lines," as they are still called, were found to range in intensity from the most delicate hairlike threads to strong black lines of appreciable width, scattered throughout the spectrum from red to violet. Their sharpness and easy visibility were undoubtedly due to the perfection of his optical parts and the fact that his slit, though a little wider than Newton's narrowest opening, was placed at a distance of 24 feet from the prism. The observations were made through a small telescope, mounted just behind the prism on the circle of a theodolite, which permitted accurate angular measures of the distances between the lines to be made. Fraunhofer's instrument, which constituted the first spectroscope, thus not only served for the discovery of the lines, but showed their positions in the spectrum to be fixed and pointed the way to the present era of high precision measurements. Fraunhofer was the first to observe these same lines in the spectra of *Venus* and the Moon, and to find that while the spectra of some stars were similar to that of the Sun, others showed marked differences. He even concluded that the lines must be due to some absorptive action in the Sun and stars, but he did not determine its nature, though he was very close to Kirchhoff's discovery when he detected the agreement in posi-

[12]Herschel, *Philosophical Transactions of the Royal Society*, 1800.
[13]Ritter, *Gilberts' Annalen*, Vol. 7, p. 527, 1801.

tion of the double bright sodium line with the double dark line in the solar spectrum which he had named D[14].

I must leave the reader to look up the further progress of spectroscopy in its nascent stages during the first half of the nineteenth century, and pass on to the epoch-making discovery of Kirchhoff in 1859, which I give in his own words:

"In order to test in the most direct manner possible the truth of the frequently asserted fact of the coincidence of the sodium lines with the lines D, I obtained a tolerably bright solar spectrum, and brought a flame coloured by sodium vapour in front of the slit. I then saw the dark lines D change into bright ones. The flame of a Bunsen's lamp threw the bright sodium lines upon the solar spectrum with unexpected brilliancy. In order to find out the extent to which the intensity of the solar spectrum could be increased, without impairing the distinctness of the sodium lines, I allowed the full sunlight to shine through the sodium flame upon the slit, and, to my astonishment, I saw that the dark lines D appeared with an extraordinary degree of clearness. I then exchanged the sunlight for the Drummond's or oxy-hydrogen lime-light, which, like that of all incandescent solid or liquid bodies, gives a spectrum containing no dark lines. When this light was allowed to fall through a suitable flame coloured by common salt, dark lines were seen in the spectrum in the position of the sodium lines. The same phenomenon was observed if instead of the incandescent lime a platinum wire was used, which being heated in a flame was brought to a temperature near to its melting point by passing an electric current through it.

"The phenomenon in question is easily explained upon the supposition that the sodium flame absorbs rays of the same degree of refrangibility as those it emits, whilst it is perfectly transparent for all other rays."[15]

By repeating this famous experiment for himself, the amateur may best acquire his first working knowledge of the powerful method that reveals the nature and evolution of the Sun and stars.

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[14]See Roscoe, Schellen, and Kayser for brief accounts, or Fraunhofer's *Gesammelte Schriften* for the interesting details.

[15]Kirchhoff, *Researches on the Solar Spectrum and the Spectra of Chemical Elements*, translated by Roscoe from the *Transactions of the Berlin Academy* for 1861. Reproduced in part in Roscoe's *Spectrum Analysis*.